



ERDC WQTN-AM-16  
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## Planning Guide for Fish Passage at Pittsburgh District Dams

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### INTRODUCTION

**Background.** The US Army Engineer (USACE) District, Pittsburgh (LRP) is preparing the "Upper Ohio Navigation Study, Pennsylvania" Feasibility Study and Integrated Environmental Impact Statement (EIS). This study will examine alternatives for replacing aging navigation locks on the three uppermost navigation facilities on the Ohio River: Emsworth, Dashields, and Montgomery (EDM) Locks and Dams. Specifically, LRP has recommended replacing the 56-ft-wide auxiliary (riverside) lock at each facility with a new 110-ft-wide main chamber. This action will require encroachment into the dam, eliminating one gate each at Emsworth and Montgomery gated dams, and a section of the Dashields fixed crest dam. The plan at Dashields includes a new gate for additional flow capacity. LRP was directed by the USACE Great Lakes and Ohio River Division (LRD), through the Ohio River Mainstem System Study, to consider fish passage strategies as part of this study. LRP staff, with assistance from U.S. Fish and Wildlife Service biologists and engineers, determined that separate fish passage facilities for these dams were infeasible. However, it was also determined that fish passage could possibly be improved by modifying design features of the replacement navigation facilities themselves. LRP staff has recommended further consideration of fish passage in the Preconstruction Engineering and Design (PED) phase, which will occur after completion of the Feasibility Study and Integrated EIS. The intent, consistent with the Corps' Environmental Operating Principles and good environmental design, is to consider navigation design features that may limit upriver movement of nonnative species, but facilitate movement of both commercial traffic and native fishes. Modernizing outdated navigation locks will present an opportunity to evaluate design or operational features at the EDM facilities during PED phase, supporting LRP's commitment to evaluate fish passage. LRP envisions that the upstream fish passage strategies considered for these three projects would be broadly applicable to all inland river navigation facilities.

**Goal.** This technical note supports LRP's intent to consider fish passage in the PED and EDM phases of project planning as conveyed via a WOTS request from Tom Maier of LRP to Dr. Patrick Deliman of ERDC dated 01 September 2011 and supplemented by additional information from an email from Conrad Weiser dated 28 February 2012. The information used to prepare this document was obtained from the peer-review literature and reports produced by government agencies. Subsequent sections of this note address the following four objectives as identified in the original request:

- 1) identify previous or ongoing engineering and/or biological research focusing on fish passage, specifically with structural navigation lock or gated dam design modifications, and secondarily, with navigation lock or gated dam operational modifications;

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- 2) consider aquatic nuisance species (ANS) issues;
- 3) assess the potential of this line of thinking; and
- 4) suggest how ERDC would approach this study in support of LRP PED efforts.

## **STRATEGIES FOR UPSTREAM FISH PASSAGE AT A NAVIGATION LOCK AND DAM**

**Previous studies at navigation locks and dams.** In addition to Knights et al. (2003), which described fish passage opportunities at Ohio River mainstem dams, three major studies and several minor studies of fish passage at dams similar in some respects to the three LRP systems described above were identified. The three major studies that supplement Knights et al. (2003) include the Upper Mississippi River (UMR) and Illinois Waterway (IWW) (Wilcox et al. 2004; Zigler et al. 2011); the Tennessee River (Scott and Hevel 1991), and Lock and Dam 1 on the Cape Fear River (North Carolina) (Moser et al. 2000, CZR Incorporated 2002). The most comprehensive feasibility studies for fish passage were conducted at the feasibility level (Wilcox et al. 2004) for the UMR and IWW. The interim report prepared by Wilcox et al. (2004) appears to be the most useful of the three supplementary documents for the Ohio River feasibility study because the UMR and Ohio River Basin are within the same basin and therefore largely share the same fish communities. However, no fish passage structures have been constructed in the UMR and IWW although fish are known to pass upstream under many flow and operational conditions at most locks and dams, primarily through roller or Tainter gate bays. In contrast, upstream fish passage through navigation facilities has been described for the Tennessee River and quantified for the Cape Fear River (Moser et al. 2000). Useful information that occurs in each of these studies is applicable to the Ohio River. Additional studies that are more anecdotal in nature were performed for the St. Stephens Lock and Dam (South Carolina Department of Natural Resources 2009), the Illinois Waterway (Keevin et al. 2005), and the New Savannah Bluff Lock and Dam (Bailey et al. 2004).

Unless specific passage strategies are provided, upstream migrating fish can only pass through a typical navigation lock and dam via four possible routes:

- 1) through the lock chamber in a manner similar to ship lockage,
- 2) through the lock filling and emptying culverts (or in combination with lock chamber passage),
- 3) through the dam gate bays (either roller gates, lift gates, or Tainter gates) when water velocities have slowed sufficiently, or
- 4) by swimming over the dam spillway (either as a fixed crest dam or supplemental weir at a gated dam; this route is seldom observed and will not be discussed).

Existing constraints at each of the three Upper Ohio projects eliminate route 4 from the list so that the remaining viable options for upstream fish passage must focus on routes 1, 2, and 3.

**Potential for passage through the lock chamber.** Fish are known to concentrate in lock chambers in large numbers in the Ohio River (Ventorini 2011, Thomas et al. 2004). Fish are thought to pass through the locks and dams on the Mississippi River, although specific studies have not been conducted to evaluate the efficacy of lock passage, such as determining the rate of passage or conditions under which fish of different species will enter the lock chamber, remain in the lock chamber until the downstream miter gates close, and then exit through the upstream

miter gates after they open. However, there is no reason to suspect that fish will not pass through a lock and dam, particularly if specific operations are developed to optimally pass fish upstream.

Lock and Dam 1 in the Cape Fear River is a small, relatively low-head dam. For a number of years, the only viable route for fish to pass Lock and Dam 1 was through the lock chamber. For this reason, the lock chamber at this location has been studied in greater detail than other sites at this location. These studies led to the development of fish locking procedures that appear successful, in that they pass relatively large numbers of American shad and some other species. These fish locking procedures have been used as an interim measure until the recent completion of a permanent fish passage facility at this dam in conjunction with mitigation efforts for the Wilmington Harbor Deepening project.

These procedures are described below because they may have application to the Upper Ohio River. Initially, operators would attempt to attract fish with the following sequence of steps:

- 1) Close both upstream miter gates and then open both downstream miter gates.
- 2) Open smaller orifice gates at the base of each upstream miter gate to create an attracting flow through the lock chamber.
- 3) At the end of a cycle, close the upstream orifice gates and the downstream miter gates.
- 4) Open the upstream orifice gates to fill the lock chamber in a manner similar to a ship lockage.
- 5) Once the lock chamber is full, open the upstream miter gates and the downstream orifice gates located at the base of the miter gates to create a flow through the lock chamber to encourage fish to exit into the river upstream.

As the operators gained experience, they discovered that entry into the lock chamber was enhanced if only one of the downstream miter gates was opened while keeping the remaining gate in the fully closed position. The orifice gate in the miter gate immediately upstream of the closed downstream gate was also kept closed. The unbalanced flow creates a single large eddy within the lock chamber that retained fish more efficiently than the through-flow pattern of the double gate opening that was originally employed (Moser et al. 2000). It is noteworthy that a similar mode of operation (single open downstream miter gate) is used at the lock in the New Savannah Bluff Lock and Dam (Bailey et al. 2004). The substantial increase in passage efficiency that occurred in the transition from the double- to single-gate deployment is important because it illustrates the critical effect of relatively small design elements or operational procedures on upstream passage efficiency. The tight relationship between the details of design and operation of the lock gates and orifice gates with passage efficiency suggests that relatively small changes can make big differences on passage efficiency. LRP has come to similar conclusions based on their experiences with fish lockages at the Allegheny River locks. This suggests that small differences in design or operation may also lead to a selective fish passage strategy that targets desirable fish species at the expense of undesirable fishes (e.g., Silver carp or other nonnative fishes).

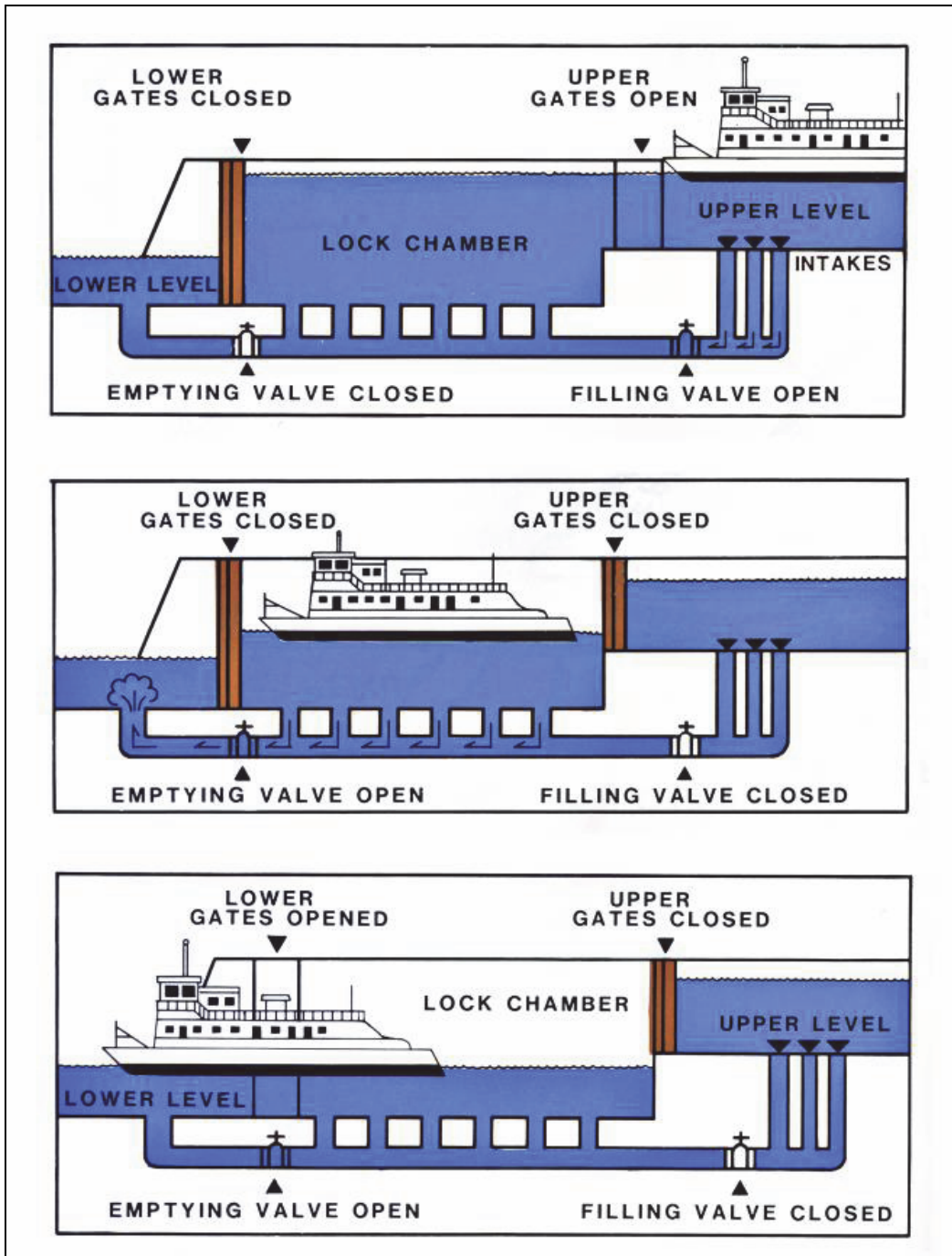


Figure 1. Illustration of downstream boat passage in a typical lock and dam. Note that both the downstream emptying valve and downstream miter are closed as a lock cycle begins. Once the boat has entered the lock chamber, both upstream miter gates and the upstream filling valve are closed and the emptying valve is open to evacuate water from the chamber. The downstream miter gate is opened when the water levels in the chamber and tailwater are approximately equal. Note also that fish can enter the lock chamber either through the open downstream miter gates or through the ports of the culverts during the later phases of the emptying cycle when water velocities in the culvert are reduced (from St. Louis District Lock and Dam 25 Factsheet).

**Potential for passage through the lock culverts.** Passage of fish through the culverts that fill and empty the lock chamber during a lockage cycle is also possible. In fact, a standard fish passage technology called a Borland Fish Lock operates on the same intermittent principle used for ship locks. The Borland Lock is simply a closed conduit that is gated at both ends and connects the headwater and tailwater of a dam. The Borland fish lock is operated much like a navigation lock to move fish upstream. In contrast, the culverts used to empty and fill the lock are not a closed system. The lock culverts are connected to the lock chamber by ports through which water flows during the filling and emptying portions of the lock cycle. The best known Borland system in the United States is located at the Corps of Engineers St. Stephens Power Plant in South Carolina (Figure 2). The operation of the St. Stephens Dam Fish Lock is described below to serve as a template for culvert operation described later in this document:

- 1) Immigrants are attracted to a downstream flow at the entrance gate of the lift.
- 2) Immigrants pass around a moveable crowder that, when engaged, forces fish into the lock chamber.
- 3) The lower gate is closed once fish have been crowded into the lock chamber.
- 4) The lock chamber is flooded and a brail basket is raised to force fish up to the lake level.
- 5) As fish exit into the lake system, they pass viewing windows, where they can be identified or counted as needed.

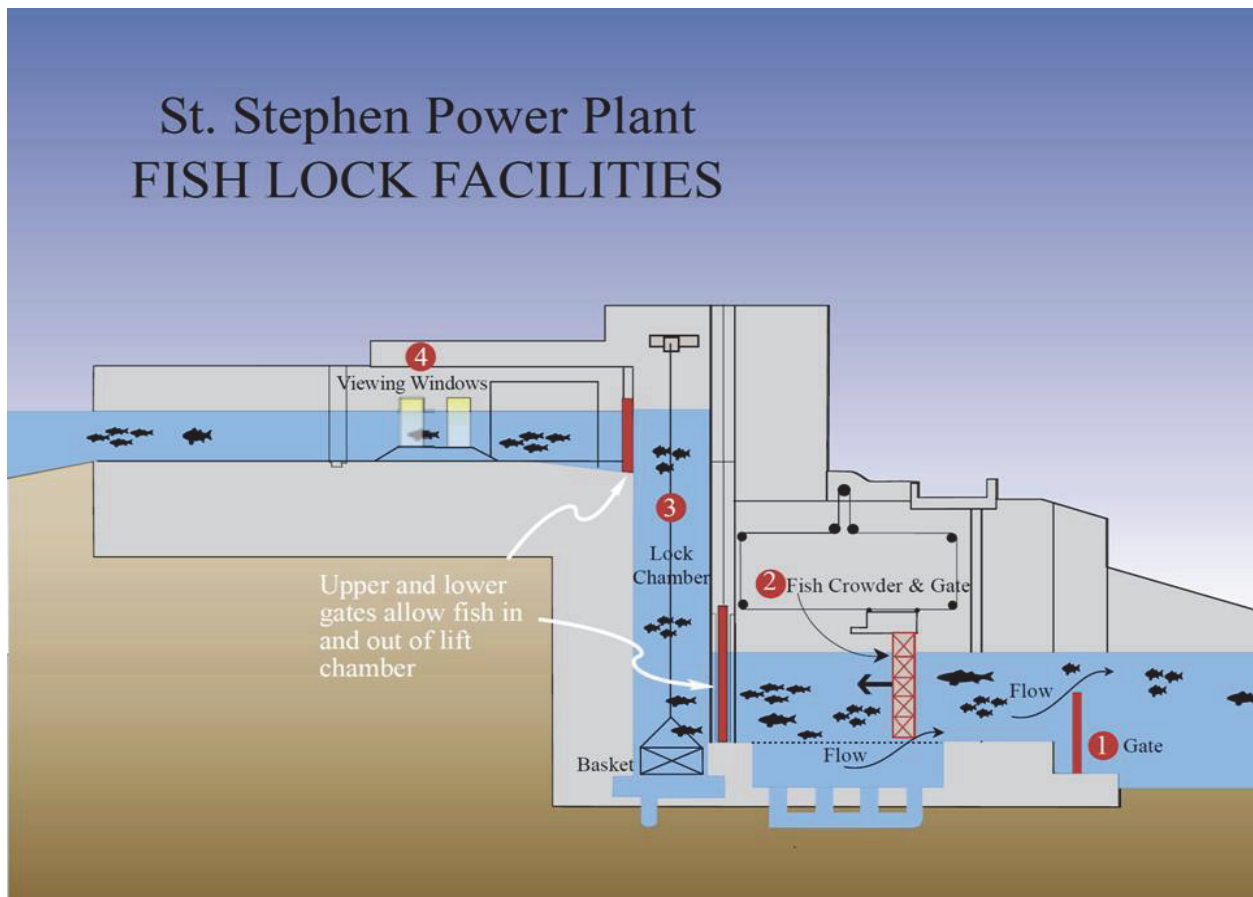


Figure 2. Fish Lock at St. Stephens Dam (from St. Stephens Dam fact sheet published by South Carolina Department of Natural Resources). Note basic similarity to Borland Fish Lock.

It should be noted that fish locks, like most fish passage systems, must be properly located, sized, and designed to be effective; there are notable examples of inefficient fish locks. Fish locks are heavily engineered structures that must accommodate the complexities of fish behavior. As a result, examples of successful and failed Borland locks can be found around the world.

Studies that document the movement of fish through the lock culverts are not common. At a number of dams in the Tennessee River, sauger use the lock culverts to gain entry into the lock chamber and then exit the lock chamber through the upstream miter gates when the gates open to pass ships (Scott and Hevel 1991). These movements have been important to maintain populations in various tailwaters of the Tennessee River. The movement is highly seasonal and corresponds to sauger spawning migrations. The success of passage is highly correlated to the design and location of the downstream culvert discharge ports. That is, ports located in deep water and near the river thalweg appear to attract the greatest number of migrating sauger. Conversely, discharge ports located in shallow water, far from the thalweg, or exhibiting a barrier to fish entry are not effective at attracting sauger. In addition, Scott and Hevel (1991) recommend the use of large numbers of smaller ports distributed over a relatively long distance as more conducive to fish passage than a single large discharge port. Sauger appear to have easier access to the lock chamber when many downstream ports are available, particularly if a low-height guide wall directs sauger to the port openings. Scott and Hevel also recommend that the upstream valve on the culverts be slightly cracked to release a small constant attracting flow at the culvert discharge ports. Note the similarity between the operation of the culvert system and operation of a Borland fish lock (Figure 2). Sauger are benthic fish; therefore, strategies that successfully pass them may hold promise for other benthic fishes such as sturgeon, catfishes, and suckers. The presence of attached mollusks is a potential danger to fish passing through the culverts. Outmigrating juvenile salmon passing through the culverts at Chittenden Locks, which connect Lake Washington and Puget Sound, are documented to be damaged by abrasion and other injuries as they contact oysters and other mollusks that encrust the culverts (Ploskey et al. 1998). A similar problem may arise from infestations of ANS species in the Ohio River that encrust culverts.

**Potential for passage through modified dam gates.** No projects were found that featured dam gates modified specifically for fish passage at low-head, low-gradient large rivers. However, fish are known to pass through the gates of navigation dams on the Mississippi River (Wilcox et al. 2004; Zigler et al. 2011) and some general conclusions can be made that probably apply to the Ohio River System of locks and dams (Knights et al. 2003). First, fish of a number of species are thought to swim through the gate bays during uncontrolled, open river conditions (gates are raised above the river and river stage is approximately the same on both sides of the dam), particularly when the gates are first raised out of the river. During this time there is likely little difference between the velocity regime within the gate bays and the open river on both sides of the dam. Large, strong swimming river fishes are thought to swim through the gate bays during this time (Zigler et al. 2011). The ability of smaller, weaker swimming fishes to pass through the dams at this time is not completely known. A useful surrogate for actual fish passage is the number of days of uncontrolled flow at each of the locks and dams. Some dams exhibit substantial number of days of open river conditions (e.g., Lock and Dam 20 is in open river conditions about 33% of the time) whereas other dams seldom or never reach open river conditions (e.g., Mississippi River Lock and Dams 1, 14, and 19 and Ohio River EDM Locks and Dams).

A number of strategies to enhance fish passage through the gate bays of the UMR were considered during planning, including (following summaries annotated from Wilcox et al. 2004):

- 1) Modifying the gate bay. Certain gate bays could be modified specifically for fish passage. These gate bays would be characterized by efforts to reduce water velocity within the gate bay either by modifying the immediate upstream forebay with chevrons or similar structures, or by installing roughness elements within the bay to reduce water velocity near the bottom or sides of the gate bays. A more extreme effort may involve locating a fishway within the gate bay, such as a rock ramp that could pass fish at times other than when the gates are raised from the river surface. In all cases, these efforts may reduce the water conveyance of the gate bay and therefore affect the discharge capacity of the spillway. Therefore, these systems must be considered in the context of existing authorized project purposes. Also, these systems must operate under a range of headwater and tailwater elevations, which can create significant design challenges.
- 2) Installing technical fishways on the spillway. Technical fishways (e.g., Denil, pool and weirs, and vertical slot) are known to effectively pass some fish species and could be installed at the spillway. However, the passage capacity of these systems is generally small and will be insufficient to sustain healthy populations in a large river for a target species. In addition, technical fishways typically pass only a narrow range of fish species and sizes, making their use to pass large assemblages of fish species problematic at best.
- 3) Installing nature-like fishways. These fishways attempt to duplicate natural streams, but of higher slope, by constructing a channel containing approximately natural bedforms. Unlike the narrow range of hydraulic features that target the requirements of only a few species, nature-like fishways provide a wide range of hydraulic conditions that are thought to pass a large number of species and a wide range of size classes.
- 4) Installing small-scale fishways at overflow spillway sections (secondary channels). Many UMR locks and dams feature secondary channels associated with the overflow spillway sections of the dam. However, no secondary channels were observed at the three Ohio River Dams considered for the feasibility report; therefore, this option will not be considered any further.
- 5) Installing large-scale fishways. These fishways extend across all or major parts of the dam and typically interfere with the existing authorized project purposes. Therefore, large-scale fishways are not discussed any further.

**ANS ISSUES:** Wilcox et al. (2004) identified ten aquatic fish species, four aquatic plant species, three mussel species, and one zooplankton species whose increasing geographical distribution may threaten the UMR and IWW. The same species are likely to also threaten the Ohio River system because the Ohio River is a tributary of the Mississippi River.

The authors believe that a carefully engineered and constructed fish passage system in the Ohio River would facilitate the passage of desirable fish species at the expense of ANS. This system would have to take advantage of the effects of small design or operation features that favor one species or group of species over others. For example, a high sill at the entrance to the St. Stephens Dam Fish Lift is thought to reduce the upstream passage of sturgeon. Sturgeon seem unwilling to enter the water column to clear this sill. Upstream American shad passage at both Cape Fear River Lock and Dam No. 1 and the New Savannah Bluff Lock and Dam is also dependent on relatively



small design and operations. This emphasizes the potential to use fish passage facilities as selective filters to pass desirable fishes at the expense of undesirable species. Perhaps small benthic fishes such as round goby and tubenose goby can be defeated by a relatively short entrance sill that still allows sturgeon passage. Likely many other possible combinations of design features and special operations can be developed that selectively pass desirable fish. However, each concept would have to be thoroughly studied and vetted before implementation. It is likely that any fish passage system will eventually pass undesirable ANS through accident, unusual hydrologic patterns, unforeseen operations or conditions, or willful intent.

#### **POTENTIAL OF STRATEGIC SELECTIVE FISH PASSAGE FOR THE OHIO RIVER:**

A review of fish passage facilities within (Tennessee River) and outside (Cape Fear River Lock and Dam No. 1 and other sites) the UMR suggests that fish passage is possible via several mechanisms: 1) lock chamber, 2) the culvert system that fills and empties the chamber, 3) a combination of 1 and 2, or 4) through the dam gate that is proposed as part of the Dashields lock replacement. Unfortunately, it is probably impossible to build a selective system that passes only desirable species, but blocks all ANS in the long term. Simply put, it is too much to expect any system to simultaneously pass and block fish at 100% efficiencies because neither blockage nor passage has ever been shown to be 100% effective (except for complete physical blockage). Wilcox et al. (2004, see Table 9) list possible means to prevent the upstream movement of ANS that may be considered for the Ohio River.

Although not commonly done, it is possible to develop systems that can redistribute fish of different species at project scales using a combination of behavioral stimuli, hydraulic features, and structural modifications. This procedure was followed by Nestler et al. (1995) at Richard B. Russell Pumped-Storage Dam on the Savannah River. The system at Richard B. Russell Dam (Nestler et al. 1996) featured high-frequency sound (Nestler et al. 1992) to repel blueback herring from entraining flows and street lights on riprap wing dikes to attract the same species to low-velocity areas along the shore. Nestler et al. (1995) assumed that predators of blueback herring would follow their prey to these same areas. In addition, the shoreline was reconfigured to modify the flow field during pumping operation to eliminate a nuisance vortex and create desirable low-velocity conditions in the tailrace areas illuminated by the street lights. Special operations were developed to minimize pumping within 30 minutes of sunrise and sunset, when fish activity was greatest. Finally, 5-cm wedge wire bar racks were attached to the trash racks to physically exclude fish longer than approximately 30 cm in length. Performance monitoring indicated that the integrated behavioral and physical barrier at Richard B. Russell Dam worked effectively based on monitoring data (Ploskey et al. 1995). The continued operation of this system from 2002 to the present suggests that relatively large-scale redistribution of fishes of different species is possible consistently across a range of operational, hydrologic, and limnological conditions.

Although this dam did not include a lock, the lessons learned from this study have application to the Ohio River locks and dams because they show that it is possible to target individual species and develop specific strategies or technologies to redistribute fish on a project scale. For example, perhaps a modified culvert system like that used on Tennessee River Dams for sauger passage could favor nighttime passage of benthic fishes. Concurrently, lighted areas far removed from either the outlets of the culverts and entrance to the lock chamber could possibly limit passage of Asian carp (if Asian carp attract to light at night) by reducing their access to the lock

chamber. The authors recommend that LRP consider the planning procedure described in Nestler et al. (1995) as a guide to evaluate the feasibility of a selective fish passage system for EDM.

### **POTENTIAL FOR FISH PASSAGE THROUGH UPPER OHIO RIVER LOCKS AND DAMS:**

An assessment of the peer-reviewed literature and government reports indicates that locks and dams outside of the Ohio River include elements of the operating fish passage systems as envisioned for the Ohio River. For example, under some conditions, sauger pass upstream into Tennessee River lock chambers through the emptying culverts. Additionally, American shad pass upstream in relatively large numbers through the lock chamber at the lightly used Cape Fear Lock and Dam No. 1 and New Savannah Bluff Lock and Dam. The light use of both locks and dams allowed lock operators the flexibility to experimentally develop and implement special fish passage operations that would conflict with normal commercial or recreational vessel passage at heavy use systems. However, it is not conclusive that such dual use (passage of both fish and navigation traffic) is impossible at heavy use systems. Rather, it is more likely that the use of lock facilities to pass fish routinely as a normal part of navigation operation has not been fully evaluated because 1) the need for such operation is relatively recent, 2) awareness that fish passage may be possible through the lock chamber and associated culvert systems is not widespread, and 3) the heavy use of Ohio River locks and dams prevented lock operators from attempting experimental fish lockages. It can be concluded that the potential for fish passage at locks and dams on the Upper Ohio River is not simply a theoretical possibility, but real in the sense that scientifically credible studies have confirmed the successful operation of parts of such systems both in the United States (Tennessee River Locks and Dams, Cape Fear River Lock and Dam No. 1, and New Savannah Bluff Lock and Dam) and internationally (Stuart et al. 2007, 2008).

This technical note concludes that developing a fish passage system while simultaneously expanding and improving locks is a potentially viable alternative and should be pursued. The authors conclude that it may be possible to build a system that preferentially passes desirable aquatic species and selectively impedes (but not completely blocks) the passage of ANS or concentrates them in places where they could be destroyed.

### **RECOMMENDATIONS FOR STUDY APPROACH**

**Introduction.** Conventional stand-alone fish passage structures are typically complicated to design and the failure rate for them is high. There are a variety of causes for these failures, but typically they can be categorized at three levels: 1) poor location of the entrances, 2) poor conditions at the entrance, and 3) conditions internal to the fishway exist that cause fish to reject the passage system. Each of these sources of failure must be addressed with specific studies. Moreover, the target species for the fishways encompass a wide array of fishes and sizes. Likely, a single system cannot pass all migratory fishes of interest so that a design featuring multiple pathways through the system should be considered. A hybrid, dual-use navigation traffic (primary) and fish passage (secondary) system exhibits the aforementioned challenges as well as additional challenges. For example, the culverts may target primarily benthic fishes (e.g., sauger, sturgeon, or catfishes) whereas the lock chamber may target fishes that swim higher in the water column (e.g., paddlefish or skipjack herring). In addition, parts of the system presently designed exclusively to support navigation traffic may be in conflict with fish passage. Common features of existing locks and dams that will likely affect passage of some species include physical

structure and hydraulic effects of the downstream approach to the lock chamber, excessively loaded barges that restrict water volume for fish, entrainment of fish through the propellers of tow boats as they maneuver within the narrow confines of the lock chamber, and the physical and hydraulic effects of the upstream approach to the lock chamber. Other effects may be discovered with further study. Of course, passage of desirable species must also be balanced against enhancing the movement of ANS.

The inherent complexity of natural rivers and the diverse behaviors of the many different species and sizes of fishes typical of large temperate rivers produce suites of uncertainties that complicate the design of effective fish passages. Resolving the high level of uncertainty associated with fish passage design begins with the water resources decision-making process itself. The preferred method for conducting program-scale fish passage planning is Adaptive Environmental Assessment and Management (AEAM – Walters and Holling 1990). AEAM organizes planning into a recursive, stepwise framework that optimizes informed environmental decision-making over time through the sequential reduction of uncertainties about fish passage. AEAM begins with the conventional water resources management steps of planning, design, and construction, but then adds a monitoring and assessment phase that informs a new cycle in the water resources development process. This “looping” (or cycling) is required because the uncertainties associated with ecological response to highly engineered structures like fishways are so great that expected benefits are seldom achieved. For example, many decades of planning and revision characterize the fish passage systems on the Columbia River. The addition of monitoring and assessment to inform future project planning functionally converts the linear planning process associated with conventional planning into a series of loops that progressively reduce project uncertainty (i.e., “learning”) as each loop is completed until project objectives are achieved. The individual steps in AEAM are well known, considered to be the preferred policy for species conservation in the USA (Williams et al. 2007), and have been applied and refined by many workers.

Key points in the AEAM cycle can be identified where investments made to maximally decrease project-threatening uncertainties can substantially reduce the number of required loops. This analysis to reduce the number of loops of AEAM is critical because each loop has an associated cost and further delays project benefits. Through aggressive reduction and management of uncertainties, AEAM can be forced to more closely resemble conventional water resources planning methods and therefore ease the burden of planning. An evaluation of AEAM identifies the following specific steps that can be taken to improve the efficiency of AEAM and increase the ability of water resources agencies to develop realistic project schedules and budgets:

- 1) develop a detailed plan that includes all program synergies and feedbacks that affect the planning process for fish passage,
- 2) create and regularly update a detailed conceptual model that embodies understanding of how the different parts of a fish pass work,
- 3) develop an institutional process where the “learning” phase of adaptive management is integrated into project planning, and
- 4) formulate a strategic monitoring plan that focuses on “learning” at the program level to reduce program-threatening uncertainties as efficiently as possible.

The most efficient way to reduce the number of loops required in AEAM is to improve the quality of the forecasts that predict fish response to fishway design features. The forecasting models must be fed with data that are as accurate and high in resolution as possible. More accurate and precise forecasts reduce the number of loops and may ultimately allow effectiveness of environmental measures to be predicted with nearly the same accuracy as more conventional hydrologic or hydraulic models. The forecast methods should also have the capacity to be easily updated as “learning” about the fishway progresses.

The authors recommend that LRP develop an AEAM plan to reduce project-threatening uncertainties. As a first step, the three uppermost Ohio River locks and dams should be evaluated to determine which offers the greatest opportunity for “learning” that could be applied to the rest of the system. In the UMR, planners included the “learning” potential of competing fish passage projects in the system prioritization. They also recommended that the first fish passage projects be constructed to be as flexible as possible so that the projects could be easily modified as “learning” progresses. They also recommended that performance monitoring be emphasized in the early projects so that later projects could be more easily optimized for fish passage efficiency.

**Eulerian-Lagrangian-Agent Methods (ELAMs).** Fish passages can be designed more efficient through the use of highly resolved and accurate forecasting tools to guide the fishway design process. These tools help reduce uncertainties through the optimal use of monitoring data and hydraulic modeling data. Eulerian-Lagrangian-Agent Methods (ELAMs; <http://EL.erd.usace.army.mil/emrrp/nfs/>) (Goodwin et al. 2006) are particularly useful in applications where there is a tight connection between fish behavior and flow pattern such as fishway design. ELAMs can reduce the uncertainties, provide a framework for evaluating projects before construction, and produce predictions on fish movement and passage that can be evaluated with traditional statistical approaches after construction. The reduction in uncertainty facilitated by the ELAM is of critical importance because a single bypass system on a major river can cost nearly 100 million US dollars. Failed systems represent a major financial loss, as well as continued severe impacts on protected fish species. ELAMs have been successfully used in a number of applications for warm-water and cold-water fish passage and restoration studies. The ELAM represents a mathematically rigorous framework for fish passage design that accentuates the strengths of:

- 1) computational fluid dynamics (CFD) modeling to help designers understand and incorporate the complex flow fields associated with river regulation structures into fish passage structure design and operation,
- 2) fish behavior studies using advanced tagging technologies to understand the sophisticated movement behaviors exhibited by migrating fish and to use this information in forecast alternatives modeling, and
- 3) agent-based modeling systems to numerically evaluate fish movement hypotheses and ultimately to construct forecast models that can be used to reduce the often considerable uncertainty associated with design and construction of fish passage systems.

An example ELAM for the Mel Price Lock and Dam on the Mississippi River illustrates the application steps and utility of the method (Figure 3). The orange traces in subplot 3B represent the swim paths made by 20 virtual benthic fish programmed to exhibit upstream migration behavior. Note that several virtual fish swim upstream through the Tainter gates. Conceptually

similar, detailed studies could be performed to evaluate fish movement through the culverts or lock chambers at Ohio River Locks and Dams as an aid to develop fish passage strategies and evaluate alternative project designs and operations.

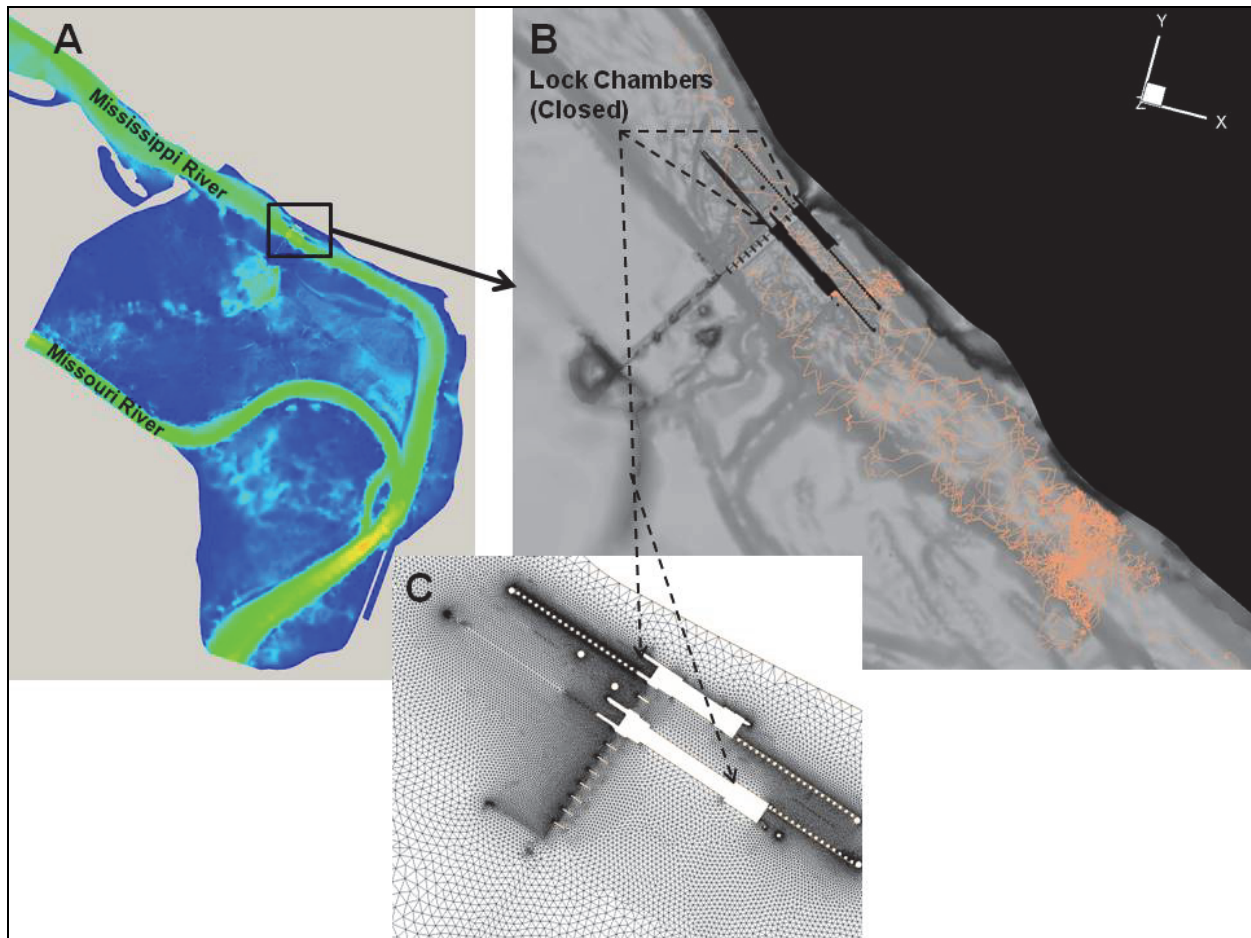


Figure 3. Example ELAM output for study of fish passage through Mel Price Lock and Dam on the Mississippi River. A: Velocity contour plot output from 2-D Adaptive Hydraulic Model (ADH) showing the general flow patterns near the confluence of the Mississippi and Missouri Rivers. B: Expanded view of the primary and secondary locks (both closed in the model). Orange traces represent the paths made by 20 virtual benthic fish. Note that some virtual fish were able to swim upstream through the dam gates. C: Mesh details for the navigation lock and gates at Mel Price.

**Recommendations for ELAM application.** A typical study requires three information sources: 1) hydrodynamic and/or water quality simulation (2D or 3D, time varying or single-flow), 2) fish movement data, and 3) behavior algorithms for the species and conditions of interest. The hydrodynamic models capture the interplay between flow and the shape of the channel, and impacts of any structures such as dams, wing dikes, and bank modifications. Information on bathymetry, flow, stage, and design drawings of the existing and proposed structures is needed to develop the flow field simulation. Water quality considerations, including temperature, can also be included, but they increase the data requirements.

Fish movement data are often available from existing monitoring activities. Typical data include electrofishing or direct capture (nets, lines, traps, etc.). These types of data are useful in understanding where and when fish of a given species (or, more generally, guild) occur under existing conditions. The hydrodynamic models and fish data are essentially overlaid to provide information to develop the fish movement model. Capturing broad fish movement patterns builds confidence that the fish movement model is providing useful information.

Behavior algorithms for fish can be highly detailed or very general. Highly detailed algorithms have high data needs and therefore are expensive. There is also a high degree of uncertainty in the final product. On the other hand, general algorithms that capture behaviors such as upstream or downstream migration and foraging can represent a large number of fishes found in the Mississippi River watershed. General algorithms implemented for fish of different sizes and swimming abilities can result in detailed spatial distributions that can be compared to existing fish data, or used to evaluate pre- and post-construction approach paths to the dam, and to formulate actual passage estimates. Thus, general behavior algorithms modified by fish size provide a means to use existing data and assess passage performance. If species-specific questions are critical, both field and laboratory studies are needed to guide more detailed modeling.

Hydrodynamic models that capture project-specific details concerning operations and alternatives can be used to forecast outcomes, rank alternatives, define field data collection needs, and integrate biology (fish distribution and guild, size, swimming capability and decision making) with the engineering models. This technique has the potential to reduce the need for post-construction adaptation, reducing project timelines and increasing success rates.

Finally, ELAMs will provide detailed information about project outcomes, with the accuracy and precision of the estimate being subject to the underlying data and cost considerations. The information developed in the model can be generalized into empirical relationships that can be used for other locations. This step will facilitate planning level studies that need to understand how different structure configurations might influence fish passage over a large number of sites.

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